

## Development of Models for the Spreading of Crude Oil

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### Abstract

*This work is carried out to investigate the spreading ability of some crude oil types by developing model equations for each of them based on the power law. Seven different types of crude oil are used for the tests. It is discovered from the results of the experiments that, among the crude oil types studied, Brass Light Mbede has the highest spreading rate while Heavy H crude oil type has the lowest. The good agreement between the experimental and estimated results from the simulation of the model equations developed reveals that the models developed describe the spreading behaviour of the crude oil types. Moreover, the results obtained from the observed F-values which were found to be greater than the critical F-value in each case of the crude oil types showed that the developed model equations are significant.*

**Keywords:** crude oil, spreading ability, model equations.

### Introduction

Crude oil is a naturally occurring liquid with a complex mixture of organic molecules, mostly hydrocarbon with varied chemical and physical properties. A precise description of the chemical composition of crude oil is not practicable because of its complexity (Amro 2004).

In the event of crude oil spill on water, a layer of oil will form and spread under the influence of wind, current, gravity and surface forces and will undergo a compositional change through dissolution, evaporation and/or surface separation. Laboratory studies have demonstrated that surface separation may be significant. It was considered of importance to oil spill clean-up planning to study the spreading of Canadian crude oils on a lake surface in the Mackenzie River delta region, which is near likely routes for oil pipelines. The drift velocity of oil spills can be estimated on the sea.

Gravity and interracial regimes may be said to exist in the spreading of oil on water, the former consisting of bulk flow and the latter of surface flow. In surface flow, some components of the oil may spread much faster than the bulk. The processes of dissolution, emulsification and evaporation will be affected by the development of spreading. Fractions of lower molecular weight, being more volatile and soluble, will preferentially be removed from the film of oil (Phillips and Groseva 1977).

Accidental oil spills have the potential to cause serious impact on the marine environment so that considerable amounts of work have been directed towards understanding and quantifying the spill processes in order to develop spill models to predict the trajectory and fate of spilled oil. When liquid oil is spilled on the sea surface, it spreads to form an oil slick whose movement is governed by the advection and turbulent diffusion due to current and wind action. Maybe due to this long tradition, Fay's empirical formulas from layer-averaged Navier-Stokes equations and their later derivatives are still sometimes considered as the state-of-the-art in oil slick modelling literature (Guo and Wang 2009).

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Knowledge of oil-spill behaviour in water is important for contingency planning at many locations (Ghannam 2003). When oil spreads on water, the process involves three different phases of matter, namely air, oil and water (Gjøsteen 2004). Spreading of oil spill on water is the horizontal expansion of the oil spill due to gravity, inertia, viscous and surface tension forces (Njobuenwu 2004). Spreading is one of the most significant processes during the early stages of an oil spill in water, increasing the overall surface area of the slick, thereby enhancing mass transfer via the evaporation and dissolution processes (Jeffery 1973; Clark and MacLeod 1977). This tendency for an oil spill to spread depends on two physical forces acting together: the force of gravity that causes the oil to spread horizontally and the surface tension of the substrate (water), which is usually greater than that of oil film floating on water, also causes the oil spill to spread (Fay 1969). Gravity and surface tension will promote the spreading of oil on a calm sea surface while inertia and viscosity will retard spreading (Fay 1971).

The work of Fay (1969, 1971) showed the existence of three stages of spreading of oil on calm water. The first stage is the gravity-inertial stage in which gravity force, the dominant driving force for spreading, is balanced by inertia force, the predominant resisting force. In the second stage, viscous force replaces inertia force as the dominant resisting force. Finally, in the third stage, surface tension force replaces gravity as the dominant promoting spreading force. A review is given in Hoult (1972), and more recent works and reviews can be found in Chebbi (2000) for the gravity inertial stage, in Buckmaster (1973) and Chebbi (2001) for the viscous-gravity stage of spreading, and in Foda and Cox (1980) and Phillips (1996) for surface-tension spreading. Including Fay's type spreading laws in modeling the fate of oil spills is shown in Shen *et al.* (1987). Even though the classical spreading equations developed by Fay form the basis for the most spreading algorithms in use today, it is widely recognized that oil spreading cannot be fully explained by these equations. Lehr *et al.* (1984) proposed an elongated ellipse along the direction of the

wind model to account for the observed non-symmetrical spreading of oil slicks. Njobuenwu and Abowei (2008) also proposed that the extent of spread  $R(t)$  obeyed the power law with respect to time, as follows:

$$R(t) = mt^n, \quad (1)$$

where  $t$  is the time,  $n$  is the power law exponent and  $m$  is the pre-exponential constant.

Oil spill modelling can be used for several different purposes, depending on which the choice of the type of the appropriate model should be made. Different models will include the description of different physical processes, which imply that they will need different extent of input data and thus the accuracy of their output results will be different. Oil spill models can be used retrospectively to analyse or reconstruct a given event. In this situation, it may be possible that all the required information is available about the meteorological conditions at the location, as well as about the characteristics of the spilled product. In this case it can be appropriate to use a very sophisticated tool that models the details of the physical process. However if some of the details of the input data are missing, the use of such a sophisticated model will invariably lead to results that will deviate from the correct ones by an uncertain value. A simpler model that only represents the most important physical processes may provide equally accurate results when some of the input data is unknown or uncertain (Sebastião and Soares 2006).

Therefore, the work is aimed to develop model equations based on the power law given in Eq. (1) for Antan Teminal, Bonny Light, Bonny Medium, Brass Light Mbede, Forcados Blend, Heavy H and Qua Iboe Light crude oil types.

## Methodology

### Experimental Procedure

The schematic representation for the set up of the experiment is as shown in Fig. 1. The crude oil types used are Antan Teminal, Bonny Light, Bonny Medium, Brass Light Mbede, Forcados Blend, Heavy H and Qua Iboe Light. The water channel was of length 3 m, width of 0.25 m and depth of 0.4 m. The channel length

was divided into equal parts of 150 mm each; each division was marked with a coloured material (Jimoh and Alhassan 2006). Before the experiment was commenced, the channel was cleaned and flushed with water to ensure that there was not any external material inside it. It was filled with water and left for some time to become calm. A predetermined quantity of crude oil sample was then released at one end of the channel with the aid of a funnel and allowed to spread over the water. For each sample, the time of spreading to each of the marked locations was noted with the aid of a stop watch and recorded. The test was carried out five times for each sample and the average time of spreading was taken for good accuracy.

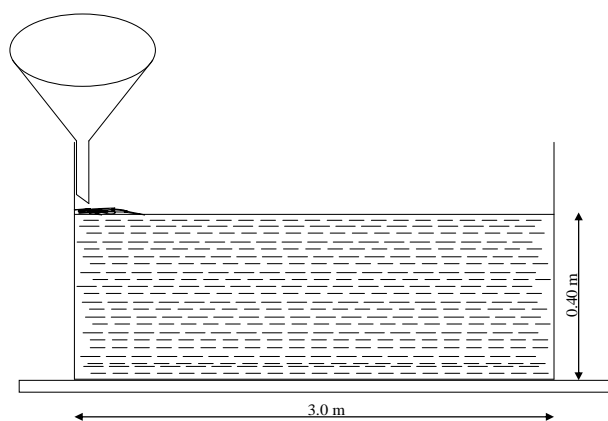


Fig. 1. Schematic of experimental set up.

### Model fitting procedure

Using the power law model proposed by Njobuenwu and Abowei (2008) shown in Eq. (1), the results obtained from the experiments were fitted in order to determine the values of the pre-exponential constant,  $m$ , and the power law exponent,  $n$  for each of the crude oil types studied in this work using a spreadsheet program.

## Results and Discussion

The results of the experiments carried out on six different types of crude oil (Antan Teminal, Bonny Light, Bonny Medium, Brass Light Mbede, Forcados Blend, Heavy H and Qua Iboe Light) in which the time taken for each crude oil to spread to some specific distances are as shown in Fig. 2. The results show that the distance spread by the oil sample

increased with increase in time. In other words, in the case of any obstruction along the path of movement, the distance of spreading of the crude oil samples investigated was found to be proportional to the time of spreading with Brass Light Mbede crude oil being the one with the fastest spreading rate while Heavy H crude oil type was found to be the slowest to spread. This relationship obtained from the experiments has revealed that the extent of spreading is a function of time.

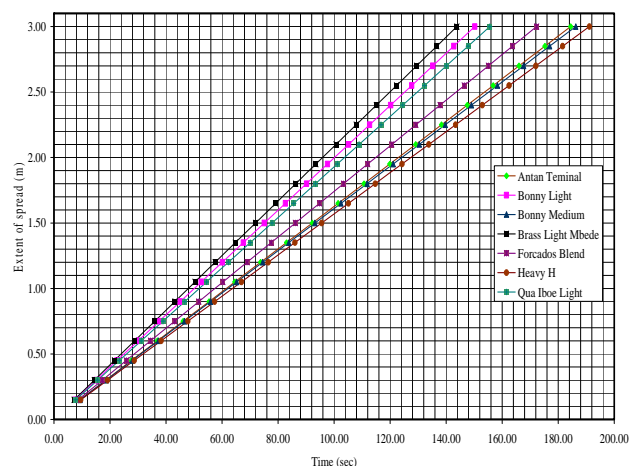


Fig. 2. Extent of spread of the crude oil types.

Having discovered that the extent of spreading is a function of time, it is important to verify the actual kind of relationship that exists between the two variables. This fact led to the use of the power law proposed by Njobuenwu and Abowei (2008) to fit the data in order to verify its compliance with the proposed model. The fitting of the experimental data shown in Fig. 2 into the power law was used to obtain the values of  $m$  and  $n$  as contained in the equation. The value of  $m$  and  $n$  for each of the crude oil types are as shown in Table 1.

Table 1. The values of  $m$  and  $n$  for the crude oil.

S/N	Crude oil type	$m$	$n$
1	Antan Teminal	0.01627	0.99995
2	Bonny Light	0.01998	0.99997
3	Bonny Medium	0.01611	1.00000
4	Brass Light Mbede	0.02086	0.99995
5	Forcados Blend	0.01742	0.99992
6	Heavy H	0.01569	1.00005
7	Qua Iboe Light	0.01928	0.99995

After obtaining the values of  $m$  and  $n$ , they were substituted into Eq. (1) to give the developed model equations as a function of the time  $t$  for each of the crude oil types, as follows:

$$\text{Antan Terminal: } R(t)=0.01627t^{0.99995}, \quad (2)$$

$$\text{Bonny Light: } R(t)=0.01998t^{0.99997}, \quad (3)$$

$$\text{Bonny Medium: } R(t)=0.01611t^{1.00000}, \quad (4)$$

$$\text{Brass Light Mbede: } R(t)=0.02086t^{0.99995}, \quad (5)$$

$$\text{Forcados Blend: } R(t)=0.01742t^{0.99992}, \quad (6)$$

$$\text{Heavy H: } R(t)=0.01569t^{1.00005}, \quad (7)$$

$$\text{Qua Iboe Light: } R(t)=0.01928t^{0.99995}. \quad (8)$$

The simulation of each of the equations (Eqs. 2 to 8) for each crude oil types was carried with the aid of a spreadsheet program and the comparison of the experimental and theoretical results obtained after the simulation are as shown in Figs. 3 to 9, where:

$R_{\text{exp}}$  = experimental extent of spread;

$R_{\text{theo}}$  = theoretical extend of spread.

As one can be observe from Figs. 3 to 9, there is a close agreement between the theoretical and the experimental results for each of the crude oil types, that is, the results obtained from the model equation were found to satisfy the experimental ones.

Apart from comparing the experimental and the theoretical results, the validity of the model equation developed for each of the crude oil types was also verified by calculating the R-square values, sum of squared values of the residuals and observed  $F$ -values. The results obtained for these parameters are shown in Table 2, where:

$R^2$  = R-square value;

$SS_{\text{res}}$  = residuals sum of squared values.

The values of the  $R$ -square which is equal to 1 for each of the crude oil types, as seen in Table 2, in part of the evidences that the model equations fit the observed data very well. Also from Table 2, the negligible values of the sum of squared values of the residuals is another reason for the good fittings between the experimental and the model results for each of the crude oil types. Finally, in order to show the significance the developed model equations as a whole, the observed  $F$ -values were calculated and compared to the critical  $F$ -value. For each of the crude oil types, it was discovered that the observed  $F$ -value was greater than the critical  $F$ -value; this implied

that the model equations developed for each of the crude oil types were actually significant.

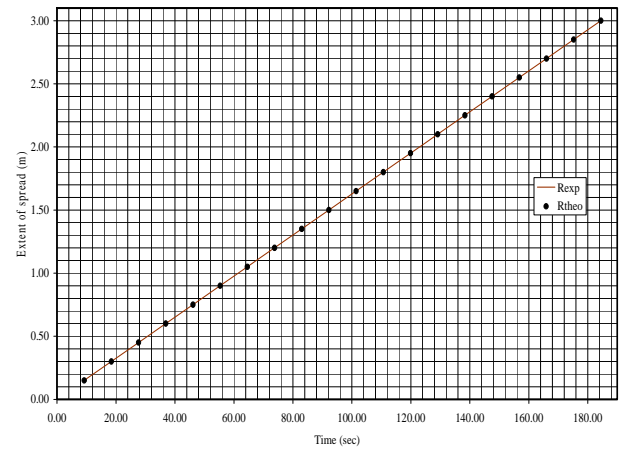


Fig. 3. Extent of spread for Antan Terminal.

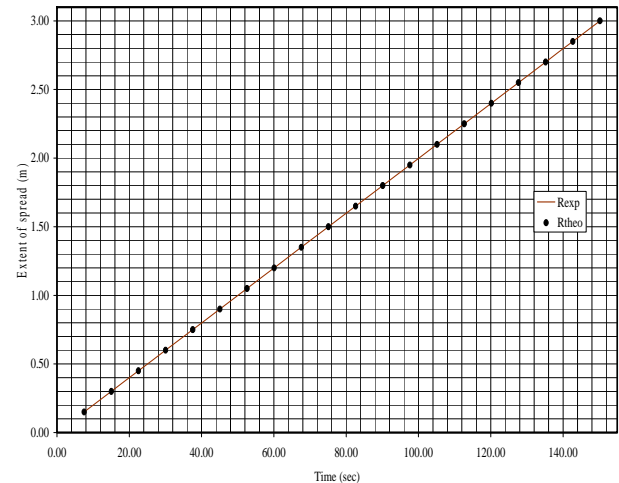


Fig. 4. Extent of spread for Bonny Light.

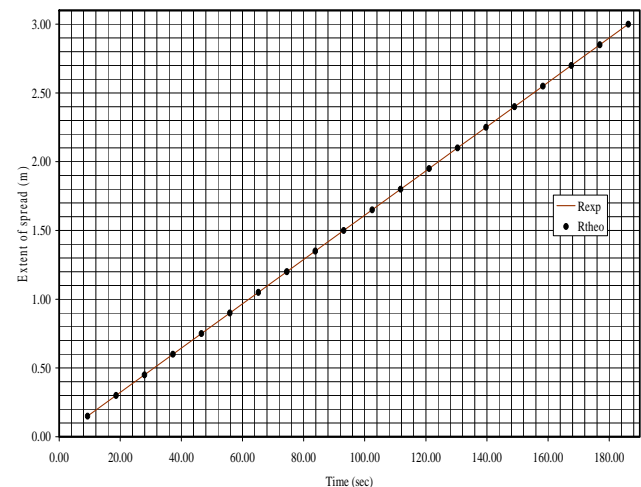


Fig. 5. Extent of spread for Bonny Medium.

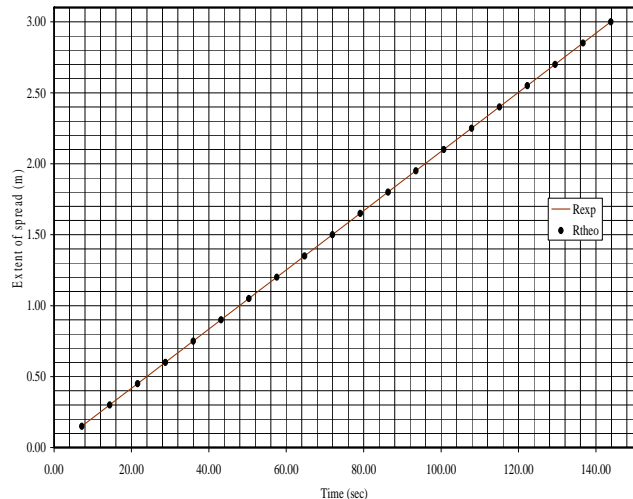


Fig. 6. Extent of spread for Brass Light.

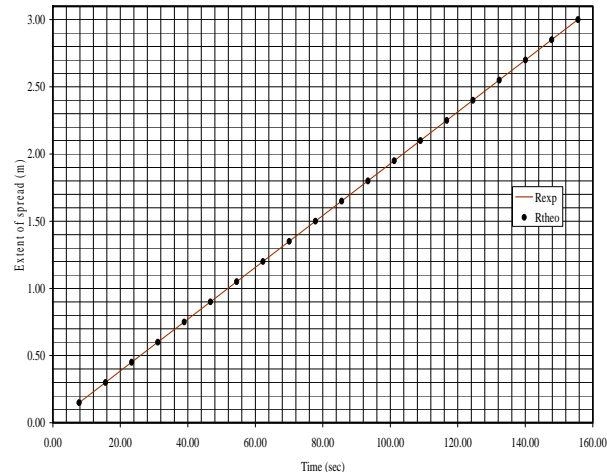


Fig. 9. Extent of spread for Qua Iboe Light.

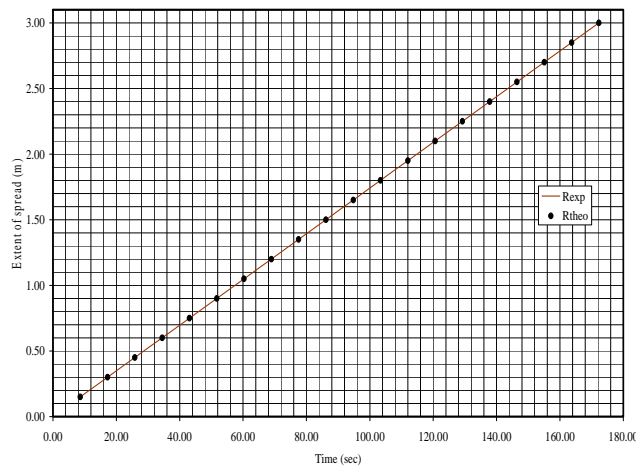


Fig. 7. Extent of spread for Forcados Blend.

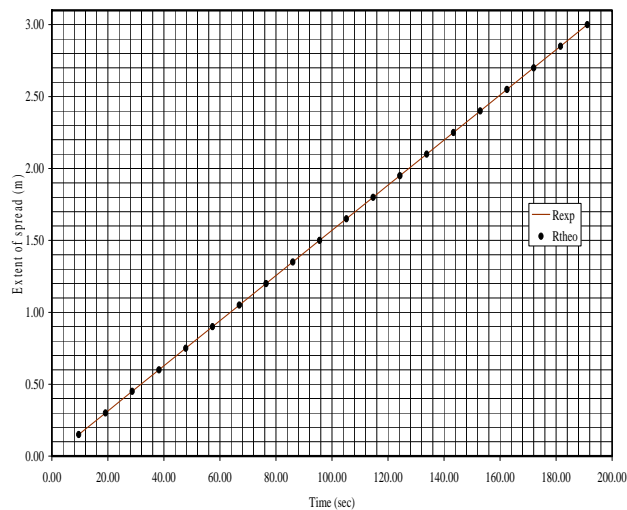


Fig. 8. Extent of spread for Heavy H.

Table 2. Validation parameters for the models.

#	Crude oil type	$R^2$	$SS_{res}$	$F$ -value
1	Antan Teminal	1	9.59E-08	2.36E+09
2	Bonny Light	1	1.61E-08	1.40E+10
3	Bonny Medium	1	1.74E-07	1.30E+09
4	Brass Light	1	1.69E-07	1.33E+09
5	Mbede			
6	Forcados Blend	1	2.00E-07	1.13E+09
7	Heavy H	1	1.46E-07	1.55E+09
	Qua Iboe Light	1	6.91E-08	3.27E+09

Conclusion

The results obtained from the spreading tests of the crude oil types carried out showed that the extent of spread is a function of time. After fitting the experimental results to the power law model, the good agreement between the experimental and the theoretical results revealed that the developed model equations were good representatives of the spreading phenomena of the crude oil types investigated. Moreover, the results obtained from the observed  $F$ -values which were found to be greater than the critical  $F$ -value in each case of the crude oil types showed that developed model equations were significant.

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